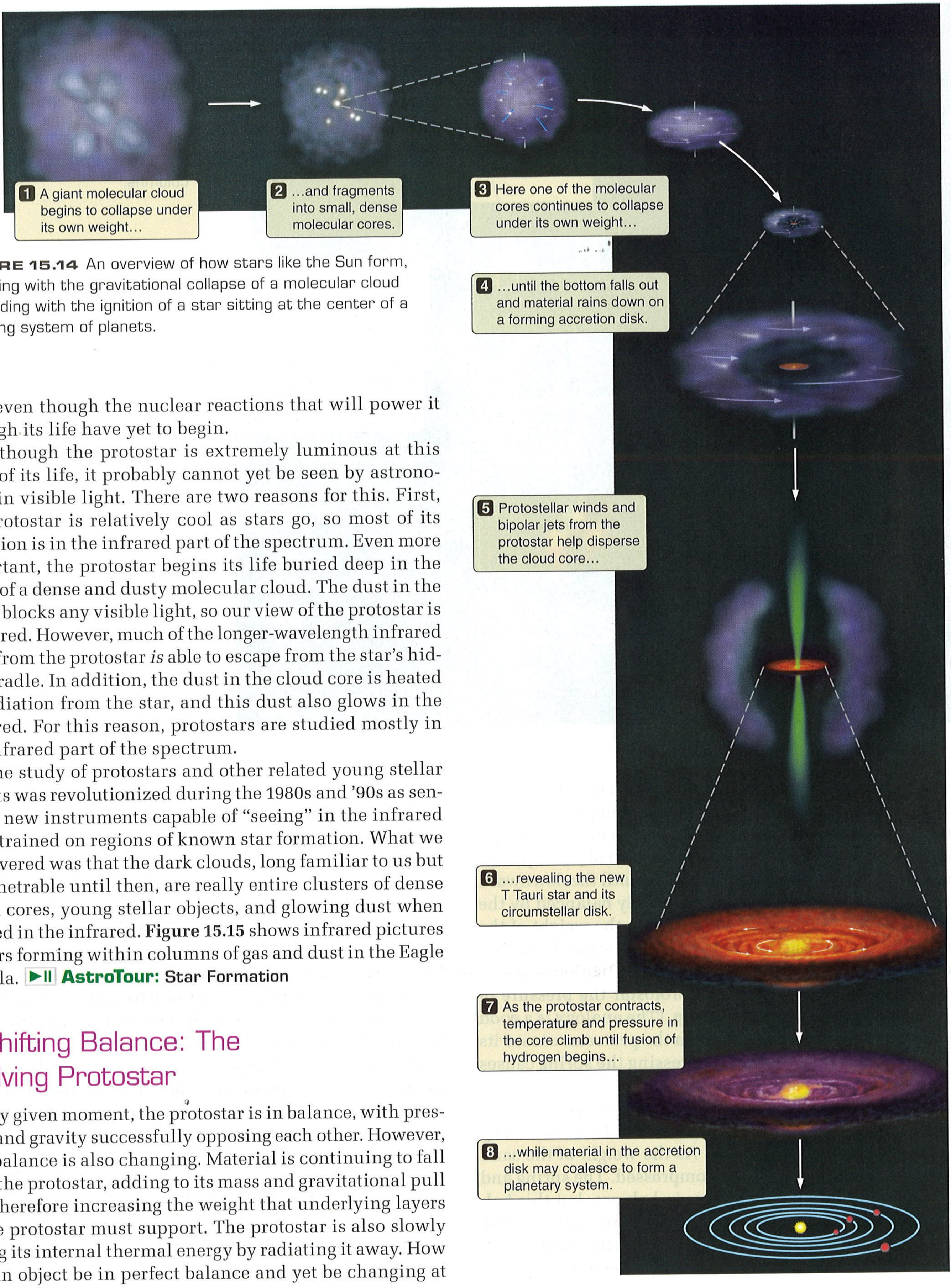


FIGURE 15.14 An overview of how stars like the Sun form, beginning with the gravitational collapse of a molecular cloud and ending with the ignition of a star sitting at the center of a revolving system of planets.

Sun, even though the nuclear reactions that will power it through its life have yet to begin.

Although the protostar is extremely luminous at this stage of its life, it probably cannot yet be seen by astronomers in visible light. There are two reasons for this. First, the protostar is relatively cool as stars go, so most of its radiation is in the infrared part of the spectrum. Even more important, the protostar begins its life buried deep in the heart of a dense and dusty molecular cloud. The dust in the cloud blocks any visible light, so our view of the protostar is obscured. However, much of the longer-wavelength infrared light from the protostar *is* able to escape from the star's hidden cradle. In addition, the dust in the cloud core is heated by radiation from the star, and this dust also glows in the infrared. For this reason, protostars are studied mostly in the infrared part of the spectrum.

The study of protostars and other related young stellar objects was revolutionized during the 1980s and '90s as sensitive new instruments capable of "seeing" in the infrared were trained on regions of known star formation. What we discovered was that the dark clouds, long familiar to us but impenetrable until then, are really entire clusters of dense cloud cores, young stellar objects, and glowing dust when viewed in the infrared. **Figure 15.15** shows infrared pictures of stars forming within columns of gas and dust in the Eagle Nebula. ▶II **AstroTour: Star Formation**

A Shifting Balance: The Evolving Protostar

At any given moment, the protostar is in balance, with pressure and gravity successfully opposing each other. However, this balance is also changing. Material is continuing to fall onto the protostar, adding to its mass and gravitational pull and therefore increasing the weight that underlying layers of the protostar must support. The protostar is also slowly losing its internal thermal energy by radiating it away. How can an object be in perfect balance and yet be changing at

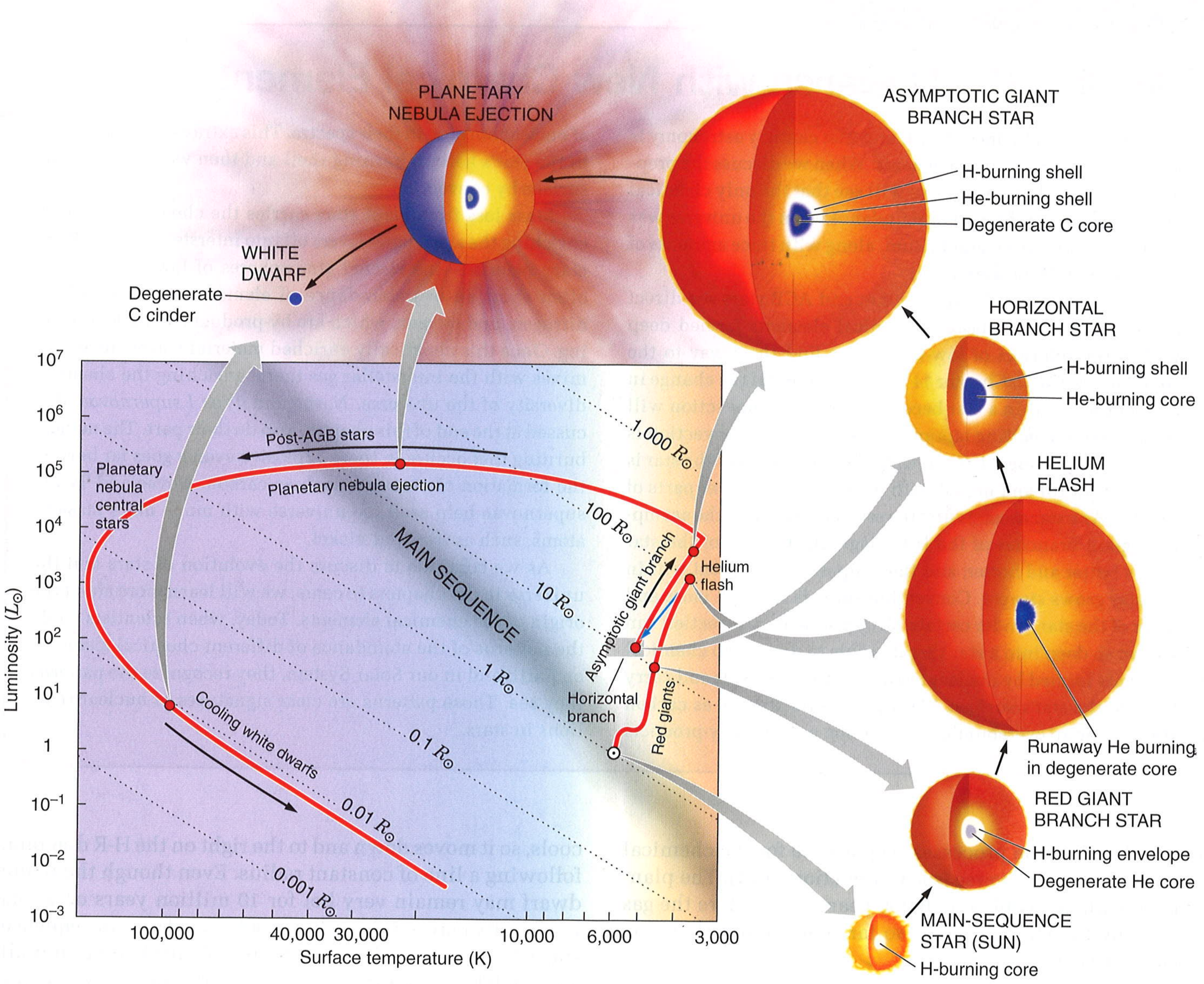


FIGURE 16.13 This H-R diagram summarizes the stages in the post–main sequence evolution of a 1-$M_\odot$ star.

white dwarf depends on many details particular to the star. Some stars less massive than the Sun may become white dwarfs composed largely of helium rather than carbon. Temperatures in the cores of evolved 2-$M_\odot$ to 3-$M_\odot$ stars are high enough to allow additional nuclear reactions to occur, leading to the formation of somewhat more massive white dwarfs composed of materials such as oxygen, neon, and magnesium. Differences in chemical composition of a star can also lead to dramatic differences in its post–main sequence evolution. Finally, we note that studies of the evolution of stars whose main-sequence masses are less than about 0.8 $M_\odot$ or so are pure theory. These stars are able to burn hydrogen in their cores for longer than the current age of the universe. No star with a mass lower than that has ever evolved beyond the main sequence except in the virtual world of a computer's calculations.

In our discussion of stellar evolution we have focused on what happens after a star leaves the main sequence. It is important, however, to remind ourselves that the spectacle of a red giant or AGB star is ephemeral. The Sun will travel the path from subgiant to white dwarf in less than one-tenth of the time that it spends on the main sequence steadily burning hydrogen to helium in its core. Stars spend most of their luminous lifetimes on the main sequence, which is why most of the stars that we see in the sky are main-sequence stars. (Were it otherwise, the "main sequence" would not be "main" at all!) In the end, though, white dwarfs will carry the day. Too faint to be noticed as we look at the sky on a clear summer evening, white dwarfs still constitute the final resting place for the vast majority of stars that have been or ever will be formed.

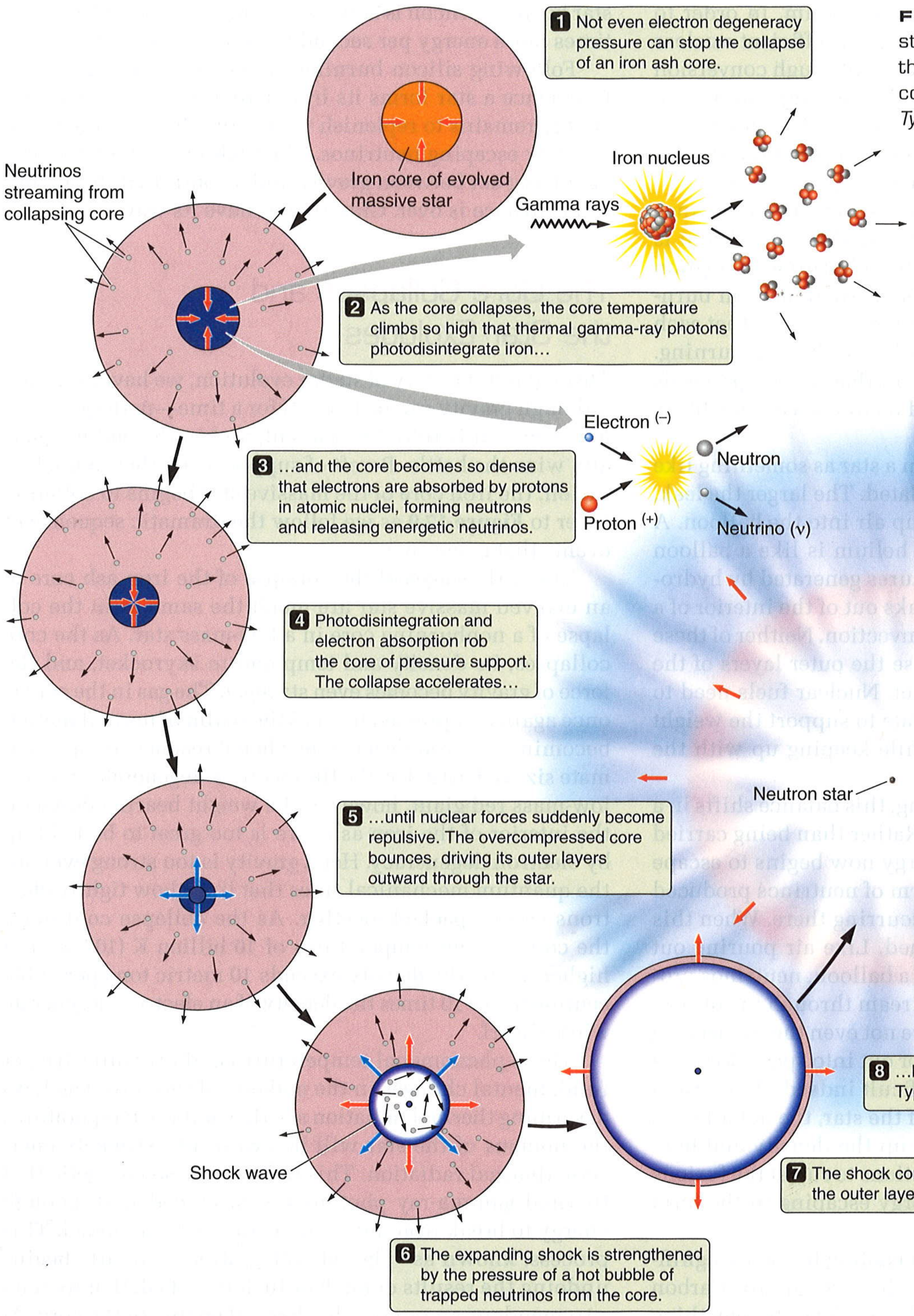


FIGURE 17.9 Shown here are the stages that a high-mass star goes through at the end of its life as its core collapses and the star explodes as a *Type II supernova*.

1 Not even electron degeneracy pressure can stop the collapse of an iron ash core.

2 As the core collapses, the core temperature climbs so high that thermal gamma-ray photons photodisintegrate iron…

3 …and the core becomes so dense that electrons are absorbed by protons in atomic nuclei, forming neutrons and releasing energetic neutrinos.

4 Photodisintegration and electron absorption rob the core of pressure support. The collapse accelerates…

5 …until nuclear forces suddenly become repulsive. The overcompressed core bounces, driving its outer layers outward through the star.

6 The expanding shock is strengthened by the pressure of a hot bubble of trapped neutrinos from the core.

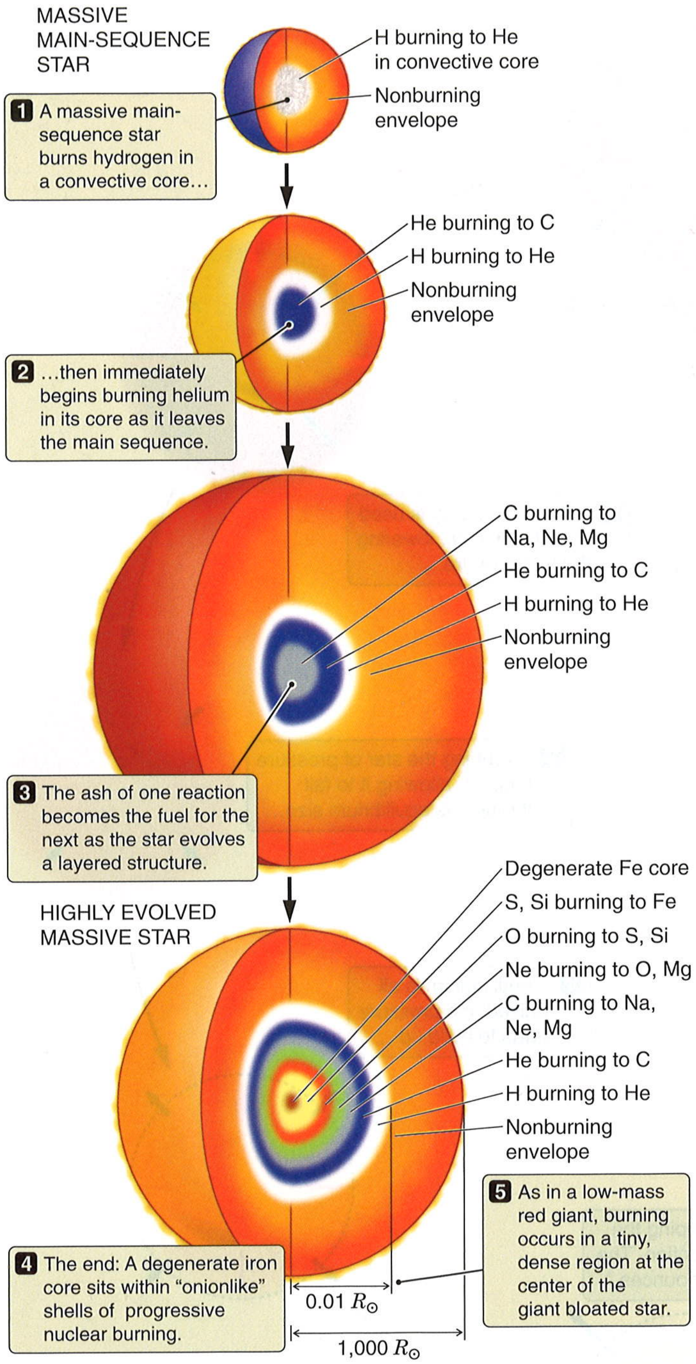
7 The shock continues through the outer layers of the star…

8 …blasting forth in a Type II supernova…

9 …and leaving behind the collapsed remains of the core, a neutron star.

The next hurdle standing in the way of the collapsing core is the force that holds atomic nuclei together. As material in the collapsing core reaches and exceeds the density of an atomic nucleus, the strong nuclear force actually becomes repulsive. Computer models say that about half of the collapsing core suddenly slows its inward fall. The remaining half slams into the innermost part of the star at a significant fraction of the speed of light and "bounces," sending a tremendous shock wave back out through the star.

Under the extreme conditions in the center of the star, neutrinos are being produced at an enormous rate. Over the next second or so, almost a fifth of the mass of the material in the core is converted into neutrinos and their energy. Most of these neutrinos pour outward through the star; but at the phenomenal densities found in the collapsing core of the massive star, not even neutrinos pass with complete freedom. A few tenths of a percent of the energy of the neutrinos streaming out of the core of the dying star is trapped



1 A massive main-sequence star burns hydrogen in a convective core…

2 …then immediately begins burning helium in its core as it leaves the main sequence.

3 The ash of one reaction becomes the fuel for the next as the star evolves a layered structure.

4 The end: A degenerate iron core sits within "onionlike" shells of progressive nuclear burning.

5 As in a low-mass red giant, burning occurs in a tiny, dense region at the center of the giant bloated star.

FIGURE 17.5 As a high-mass star evolves, it builds up a layered structure like that of an onion, with progressively more advanced stages of nuclear burning found deeper and deeper within the star. Note the change in scale for the bottom image.

Not All Stars Are Stable

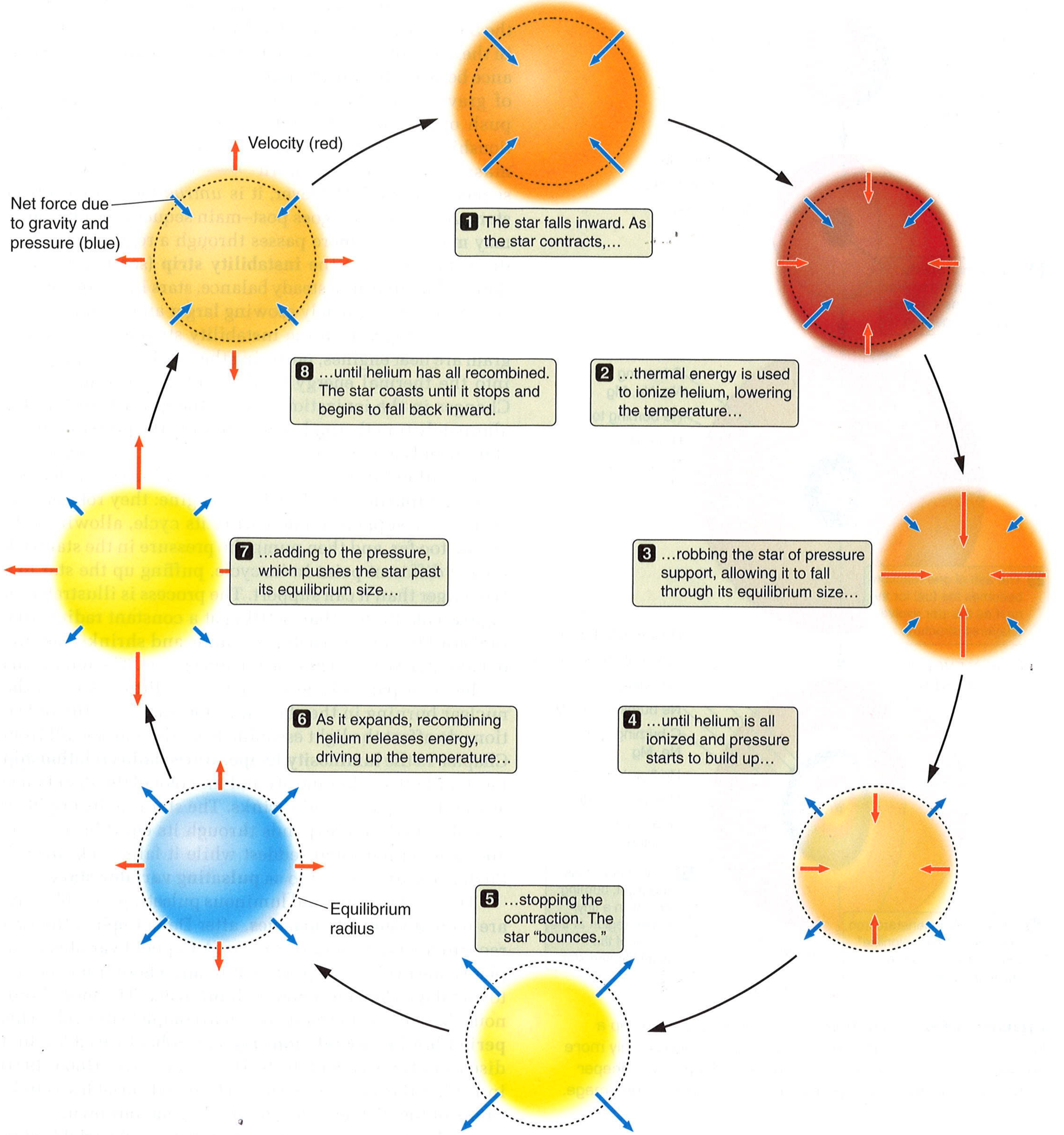
When we discussed the structure of the Sun in Chapter 14 and a low-mass star in Chapter 16, we asserted that a single stable solution always exists. Given one solar mass with a mix of 70 percent hydrogen and 30 percent helium, that mass *will* form a stable star with the structure of our Sun. As we "what if" the Sun, considering the consequences of forcing the Sun to be larger or smaller than it is, we find that changes in the star would cause it to settle back into this unique balance between the inward pull of gravity and the outward push of pressure. This relationship remains true for high-mass stars on the main sequence as well. However, it is *untrue* for many evolved stars. As a star undergoes post–main sequence evolution, it may make one or more passes through a region of the H-R diagram known as the **instability strip** (see Figure 17.4). Rather than finding a steady balance, stars in the instability strip pulsate, alternately growing larger and smaller.

Evolved stars pulsate while passing through the instability strip.

Stars lying within the instability strip of the H-R diagram are heat engines, powering their pulsation by tapping into the thermal energy flowing outward through them. Changes in the ionization state of the gas within the star alternately trap thermal energy, forcing the pressure in the star up and causing it to expand, and then they release this energy, allowing the star to contract again. These changes serve the role of the valves in an engine: they rob the star of pressure support at one part of its cycle, allowing it to shrink too far, and then pump the pressure in the star back up at a different point in its cycle, puffing up the star to a size larger than it can support. The process is illustrated in **Figure 17.6**. Rather than settling at a constant radius, like the Sun, the star alternately expands and shrinks, moving out and in like the piston of a steam engine. The pulsations in the outer parts of the star have very little effect on the nuclear burning in the star's interior. However, the pulsations do affect the light escaping from the star. Recall from Chapter 13 the **luminosity-temperature-radius relationship** for stars: both the luminosity and the color of the star change as the star expands and shrinks. The star is at its brightest and bluest while it expands through its equilibrium size, and at its faintest and reddest while it falls back inward. Such stars are referred to as **pulsating variable stars**.

The most massive and luminous pulsating variable stars are named **Cepheid variables**, after Delta Cephei, the first recognized member of this class. A Cepheid variable completes one cycle of its pulsation in anywhere from about 1 to 100 days, depending on its luminosity. The more luminous the star, the longer it takes it to complete its cycle. This **period-luminosity relationship** for Cepheid variables, first discovered experimentally by Henrietta Leavitt (1868–1921) in 1912, is the basis for the use of Cepheid variables as indicators of the distances to galaxies beyond our own.

Cepheid variables are not the only type of **variable star**. The horizontal branch of the evolutionary tracks of low-mass stars (see Figure 16.8) may pass through the instability strip as well. These unstable horizontal branch stars are known as **RR Lyrae variables** after their prototype. They pulsate by the same mechanism as Cepheid variables but are typically hundreds of times less luminous. The instability strip also intersects the main sequence around spectral type A, and many A stars do show significant variability (although



1 The star falls inward. As the star contracts,...

2 ...thermal energy is used to ionize helium, lowering the temperature...

3 ...robbing the star of pressure support, allowing it to fall through its equilibrium size...

4 ...until helium is all ionized and pressure starts to build up...

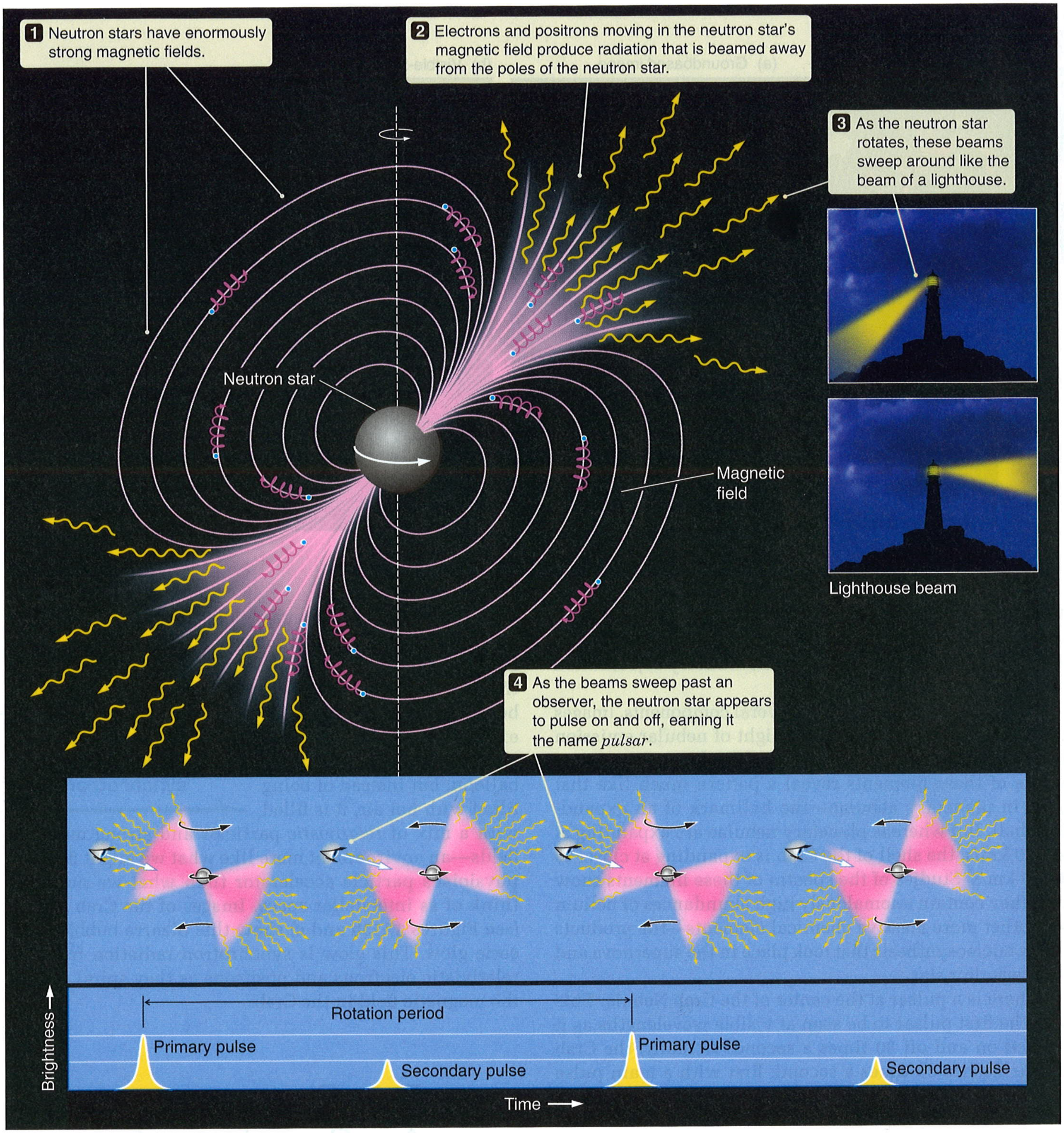
5 ...stopping the contraction. The star "bounces."

6 As it expands, recombining helium releases energy, driving up the temperature...

7 ...adding to the pressure, which pushes the star past its equilibrium size...

8 ...until helium has all recombined. The star coasts until it stops and begins to fall back inward.

FIGURE 17.6 In a pulsating Cepheid variable, ionization of atoms in the star's interior acts like the valves in a steam engine, alternately allowing the surface of the star to fall inward, and then pushing it back out again. (Color changes shown here are greatly exaggerated.)



1 Neutron stars have enormously strong magnetic fields.

2 Electrons and positrons moving in the neutron star's magnetic field produce radiation that is beamed away from the poles of the neutron star.

3 As the neutron star rotates, these beams sweep around like the beam of a lighthouse.

4 As the beams sweep past an observer, the neutron star appears to pulse on and off, earning it the name *pulsar*.

VISUAL ANALOGY **FIGURE 17.14** As a highly magnetized neutron star rotates rapidly, light is given off, much like the beams from a rotating lighthouse lamp. From our perspective, as these beams sweep past us the star will appear to pulse on and off, earning it the name *pulsar*.